Real-Time Measurements of Sediment Modification by Large Macrofauna

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LONG-TERM GOALS

Marine sedimentary infauna alter acoustic properties of sediments by creating voids and air bubbles, manipulating grain and shell distributions, moving interstitial fluid and creating surface roughness elements. Our prior results from ONR support suggest that conceptual models of organism modifications of solute flux are grossly inaccurate in both diffusion-dominated and advectively permeable environments. The porewater transients detected by our pressure transducers represent several cm of water pressure in many cases and result in advective flows. The strong, pulsed flows imposed by organisms are radically different from the current models of irrigation-mediated transport or surface-driven porewater advection, a result with significant implications for bacterial transformations and particle movements. Our research addresses fundamental questions in benthic biological oceanography with significant relevance to naval operations: what factors affect infaunal activity patterns and movements and how do these processes affect sediment acoustic properties? Our research has three thrusts: (1) the development of new technologies to measure, in real-time, organism movements and the effects of these movements on the pressures, voids, fluid flows and surface roughness elements of nearshore sediments; (2) the experimental determination of the ecological and geochemical factors, including organism density, resource availability, and the concentration of metabolites in porewater that affect rates of organism movement; and (3) the evaluation of the ecological and geochemical consequences of these interactions. These results will allow us to link the behaviors and dynamics of macrofauna to ecosystem-level processes in coastal habitats and to the predictability of acoustic properties of operational importance to the Navy.

OBJECTIVES

This project is centered on expanding (1) our sensor capabilities to allow remote detection of organism activities in sediments utilizing porewater pressure transients and optical methods; (2) the number of species, water depths and types of sedimentary environments within our database; (3) our ability to

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measure labile organics optically; and (4) the linkages of organisms' activities to alteration of the acoustical, geochemical, and biotic properties of sediments.

The research also fulfills three important goals within ONR's Biological and Chemical Oceanography Program: (1) to enable the prediction of the distribution and abundance of biota and their interactions with biogeochemical processes in shallow water sediments, (2) to understand how biota affect the acoustical properties of operational importance to the Navy, and (3) to explore new instruments to sample and observe biological processes.

APPROACH

Our experimental approach is centered on the supposition that relocation of individuals and biogenic modification of the physical and chemical matrix are driven by interactions among organisms and their biological and geochemical environment. Our experimental approach, in combination with new technologies, has provided a mechanistic understanding of organism-sediment interactions that highlights the importance of ecological processes in sediments and has broad scale significance for coastal processes. We are particularly interested in species that are widely distributed, common and large such as *Arenicola marina* along the European coast, *Abarenicola pacific* in the northern Pacific, several thalassinid crustaceans and a variety of tellinid bivalves. We are focusing on related species where we can ask whether similar behaviors by comparable body forms result in predictable signals and associated sediment alterations. We are particularly interested in *Arenicola marina* both as a comparison to *Abarenicola pacifica* and because of the extensive literature on its impacts. We are focusing on several tellinid bivalves for similar reasons.

Our initial research confirmed that pressure sensors could detect infaunal activities in unrestrained individuals in the field and that we could differentiate among activities and species (Wethey and Woodin 2005). We developed differential pressure transducers which allow deployment at greater depth, have greater sensitivity and are small, allowing us to deploy them in two-dimensional arrays.

Progress in the Marinelli/Waldbusser lab has focused on technique development and synthesis of data from previous experiments that reveal additional complexities concerning organism-sediment-flow interactions. Waldbusser is leading the technology development. The overall goal is to develop technologies that allow us to capture sediment heterogeneities in a more dynamic mode, to link specific organism activities to physical and biogeochemial properties and to examine the spatial and temporal dependence of these processes. To this end we are using a spectrofluorometer with a fiber optic sensor for exploration of surface detrital flux to depth in sediments plus benthic surface fluorescence mapping techniques, using excitation and barrier filters on a digital camera. Both of these approaches add a comparative element to the optode technologies discussed below and provide a different spatial and temporal scale of observation that can be used in longer term experiments.

Laboratory experiments allow a mechanistic view of how infauna interact with physical and biogeochemical properties of sediments. Field experiments by Waldbusser using gel diffusers as well as a new sediment image profiler have focused on the role of infauna on porewater advection rateand subsequent modification of biogeochemical signals? These experiments help place our laboratory measurements in a broad environmental context.

Planar optode technology in combination with our pressure sensors and video techniques has the potential to yield information on nutrient fluxes driven by pressure pulses due to organism behaviors.

Nils Volkenborn (formerly of the Alfred Wegener Institute for Polar and Marine Research and now a postdoctoral fellow with Woodin) and Lubos Polerecky (Microsensors Group, Max Planck Institute for Marine Microbiology) are collaborating with us on using oxygen optodes to explore the effect of pumping by *Arenicola marina*, *Abarenicola pacifica,* and *Macoma nasuta* on nutrient flux in sediments differing in permeability. In addition in collaboration with George Matsui and Rick Lovell, both microbial ecologists at USC, we have developed an artificial lugworm, the robo-lug, using computer controlled peristaltic pumps which can simulate both the magnitudes and directions of all the behaviors seen in the arenicolids, allowing considerable experimental flexibility in asking questions about effects on electron receptors, microbial remineralization rates, etc.

Our field measurements of advective forces associated with activities of large abundant infauna are used to confirm the laboratory data. We used areas from which large infauna have been excluded so that the biogenic hydraulic head causing advection could be measured. Nils Volkenborn and Karsten Reise (Alfred Wegener Institute for Polar and Marine Research) allowed us to use their long term exclusion experiments (20 m by 20 m) involving large arenicolid polychaetes at Sylt Germany and we have developed a continuing collaboration. All of these results will have strong implications for physical-chemical biological coupling in the coastal ocean and the degree to which it is pulsile, local and density dependent.

WORK COMPLETED

- We have pressure and video recordings of two arenicolid polychaetes. *Abarenicola pacifica* is abundant from northern California to Japan while *Arenicola marina* is often the infaunal dominant on the coast of Europe. Similar behaviors by the two species result in similar pressure waveforms.

- In *Arenicola marina*, we have measured the advective forces associated with behaviors in the field and have mapped those forces using a combination of modeling and pressure sensors.

- We have successfully deployed our differential pressure sensors in the field.

- We have concluded that due to the forces involved and the absence of differential accelerometers with the necessary sensitivity that we will be unable to detect biotic driven transients on the accelerometers.

- We have completed several sets of complementary experiments to investigate nonlinearities in the magnitude of sediment-seawater exchange rates as a function of density and activity of infauna.

- We have expanded our use of pressure sensors to several common tellinid bivalves and some behaviors such as burrowing look strikingly similar while others do not.

- We have calibrated the spectrofluorometer with its chlorophyll sensor and find a reasonable relationship between the output signal and direct measures of chlorophyll fluorescence. These measurements include calibration solutions as well as in situ measurements.

- Benthic chlorophyll mapping techniques have been successfully developed.

- Field experiments using gel diffusers and testing the role of advection relative to infauna with different activity rates and burrow types have been completed.

- Experiments testing the role of density dependence and food on biogeochemistry have been reanalyzed to reveal larger scale temporal differences in our earlier findings.

- Using a combination of oxygen planar optodes, video, ultrasound, and pressure sensors we have shown how porewater exchange changes as a function of hydraulic activities of *Arenicola marina* and the degree to which this is influenced by differences in sediment permeability.

- Experiments with a variety of infaunal bivalves from relatively sedentary large suspension feeders such as *Panopea abrupta* (geoduck) and *Mya arenaria* to more mobile tellinid bivalves reveal dramatic advection of subsurface porewaters during activities such as rapid valve closure during pseudofeces expulsion.

RESULTS

A major thrust of this project was to ask whether calculations of the sphere of influence of large hydraulically active individuals such as *Arenicola marina* was restricted to the area directly in contact with the individual and its burrow. Without knowledge of the lateral impact on sediment properties one cannot estimate the importance of biota as drivers of sediment properties or assemblages. We have now shown that the radius of spheres of influence in the field is often 40cm and the area of influence defined as the region with at least 10% turnover of porewater per day is a spheroidal region 18 cm in radius. We predicted this with numerical models and now have verified those model results with field measurements (Wethey et al. 2008).

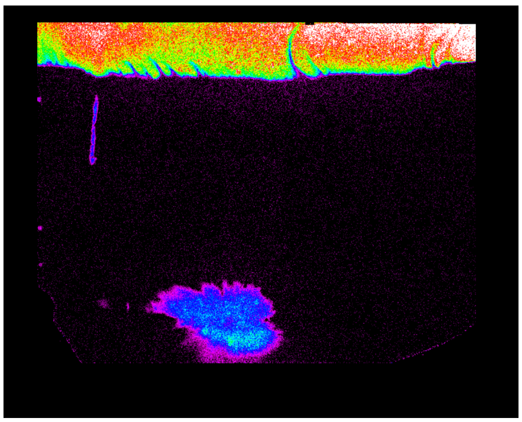
Using optodes and pressure sensors in collaboration with Lubos Polerecky at the Max Planck Institute for Marine Microbiology and Nils Volkenborn at the Alfred Wegener Institute for Polar and Marine Research we have now confirmed that tail to head pumping in *Arenicola marina increases* porewater pressure causing porewater to flow laterally and vertically away from the burrow and is accompanied by an increase in the availability of oxygen at depth as seen on the optode images. Head to tail pumping *decreases* porewater pressure as evidenced by reduction in baseline pressures in our measurements and results in entry of oxygenated water into sediments across wide areas of sediment surface. These effects change as a function of sediment permeability which affects the distances over which porewater pressures are altered by animal activities. In very permeable sediments porewaters exit the sediment surface as a sheet while in less permeable sediments plumes of anoxic porewater are seen, presumably exiting via macropores as is seen in Fig. 1A. The oxygenated water at depth appears as bright blue then violet with the anoxic porewater plumes as blue/purple.

Like the arenicolid polychaetes, tellinid bivalves are common, active members of the infauna and frequently are among the biomass dominants. Using a combination of optodes and pressure sensors we have examined the behavior of one tellinid *Macoma nasuta* in several different sediments. We have make similar observations in New Zealand on another tellinid *Macomona lilana* in collaboration with Simon Thrush and Judi Hewett at NIWA. In both cases the tellinids move their siphons to allow feeding in new locations but rarely move the body. Siphon movement is accompanied by water jets in the subsurface seen as pressure pulses on the pressure sensors. In both cases on the feeding siphon appears on the surface. The excurrent siphon is several centimeters subsurface so that as the individual

feeds, a bloom of oxygenated water appears subsurface and due to porewater pressurization as with arenicolids, this results in a release of anoxic porewater on the sediment surface. Both the subsurface oxygenation bloom and the surface anoxic plumes are seen in the optode image in Fig. 1B.

Field experiments using gel diffusers and porewater peepers show clearly the effect of infauna on porewater exchange. Gel diffusers with known concentrations of fluorescein lose fluorescence differentially as a function of infaunal type and density as shown in Fig. 2A and samples from porewater peepers show clearly the effect of infaunal advective forces on porewater nutrients (Fig. 2B).

A.



B.

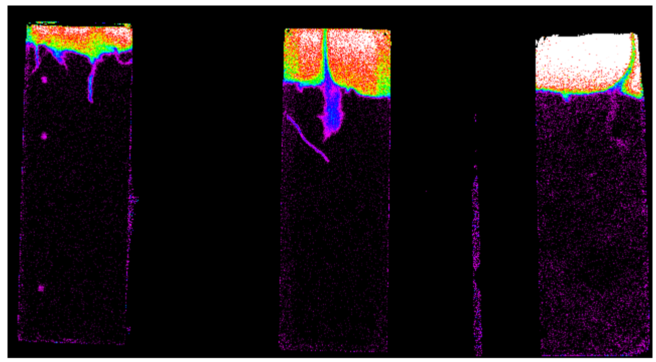


Fig. 1. A. Oxygen optode images showing result of tail to head pumping in Arenicola marina in muddy sands of relatively high permeability, such activities result in multiple plumes of anoxic porewater (blue/purple) emerging from the sediment surface.
Fig. 1. B. Oxygen optode images showing result of feeding in Macoma nasuta with the excurrent siphon located several centimeters below the sediment surface. Note oxygenation at depth as in part A and plumes of anoxic porewater emerging from the sediment surface. Brighter colors correspond to higher oxygen concentrations in the image.

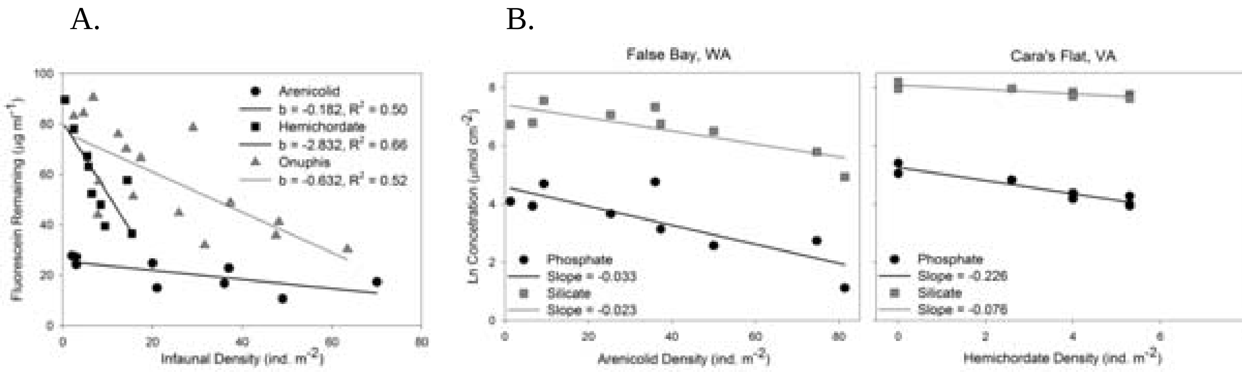


Fig. 2. A. The differential effect of different species on fluorescein remaining in the gel diffusors. Lower concentrations in the gels indicate higher rates of transport. The arenicolid (black dots) has a blind ended burrow which is open at depth, the hemichordate (black squares) has a poorly lined U-shaped burrow and the onuphid polychaete (grey triangles) has a thin sand tube. All clearly affect rates of loss of fluorescein through advection. Another onuphid Diopatra cuprea has a relatively impermeable tube with a thick rubbery lining and its densities do not correlate with fluorescein loss nor can we detect its activities via pressure sensors. B. Integrated porewater concentrations of phosphate (black dots) and silicate (grey squares) as a function of arenicolid and hemichordate density at False Bay, WA and Cara's Flat, VA, respectively.

The laboratory and field advection experiments suggest that infauna have marked effects on biogeochemical properties and sediment-seawater exchange rates at relatively slow rates of advection (Fig 1 and 2). At higher flow rates and in very permeable sediments, infaunal effects are minimized. However, field measurements suggest that in highly productive muddy sands, lower rates of advection are common and result in significant faunal manipulation of physical and chemical sediment properties both in the laboratory (Fig 1) and in the field (Fig 2).

IMPACT/APPLICATIONS

Our data consistently demonstrate the fluctuating nature of infaunal advective forces in sediments. They also strongly support the idea of positive synergistic interactions (Allee effects) among conveyor-belt feeders such as arenicolid polychaetes. This is consistent with observed patchy spatial distributions and implies non-random but predictable differential rates of sediment movement, remineralization, and bacterial activity.

RELATED PROJECTS

The work of Peter Jumars on sediment cracking by infauna and alterations of sediment textures by such activities is clearly related. We have been conversing with one another and we have provided him with video footage of sediment cracking by arenicolid polychaetes. The models of Bernard Boudreau require measurements of advective forces by organisms as well as data on frequencies of the behaviors associated with each advective event. We provided him with these.

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